



Macropore flow estimations under no-till and till systems

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ABSTRACT

The processes associated with water movement through silt loam soils involve both the flow through macropores as preferential flow or macropore flow and flow through the micropore as matrix flow. Macropore and matrix flow components were separated from total flow by a hydrograph-separation technique which used the assumption of dual porosity and a tracer mass balance. A mixture of potassium bromide was applied through a rain simulator to four plots in northern Mississippi in two rain events at 12.7 mm/h lasting 5 and 3 h separated by 6 h. The plots were either tilled or no-tilled with drains installed by two methods at the surface of the fragipan. The magnitude of water and bromide (Br^-) transported by macropore flow to a drain line were estimated and the resulting hydrographs provided an indication of the potential significance of macropore flow in transporting water and non-reactive chemicals through macropores to the shallow groundwater system. Matrix flow appears to contribute the majority of the water moving to the drains even during the early stages of the drain flow hydrographs. The no-till plots produced more macropore flow than the tilled plots, independent of how the drains were installed. Macropore flow in the drainage at any time was small as compared to the matrix flow; however it contributed a disproportionate amount of Br^- tracer. These data support the concept that models used to predict mass balances using only the matrix (Darcian) flow will underestimate those chemicals that move like bromide into the soil profile.

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1. Introduction

During the past 2 decades there has been an increased awareness of the impact of land management activities on the quality of surface water and ground water resources. Even following the elimination of many of the point sources of water contamination, there remains a persistent menace to the quality of the earth's water resources. This menace comes in the form of non-point contamination sources, which by its very name means that the sources, and maybe their mechanisms of contaminant production, are difficult to identify.

While tremendous efforts have been made to control non-point sources of surface water and ground water contamination, the query arises as to why contamination of these water resources is still so pervasive. For example, when a pesticide is known to have a short half-life and it is applied to the soil at recommended doses, one wonders how the pesticide can possibly be found later in the underlying ground water (Isensee et al., 1990). This type of water contamination may be explained by preferential flow which results in by-pass transport phenomena.

The scientific community has recognized five types of preferential flow that include macropore flow, gravity-driven unstable flow,

heterogeneity-driven flow, oscillatory flow, and depression-focused recharge. Nieber (2001) provides an overview of the scientific work that various scientists have conducted on these types of preferential flows.

One of the most prominently known forms of preferential flow is the type caused by flow in structured or macroporous soils (macropore flow). This form of preferential flow has been under intensive study since the early 1970's since the appearance of papers such as those by Thomas and Phillips (1979), Bouma (1981), and Beven and Germann (1982). While macropores may make up only a small portion of the total soil voids, they may dominate vertical flow rates during infiltration (Beven and Germann, 1982). Thomas and Phillips (1979) pointed out gravitational flow of water occurred readily in soils that were below field capacity. The presence of macropores may cause different responses from predictions based on Darcian principles when the macropores conduct water rapidly through the unsaturated soil ahead of the wetting front and the flow in the macropores is turbulent in either saturated or unsaturated zones (Beven and Germann, 1982).

Rapid fluxes through preferential flow paths such as biological macropores, worm holes, root holes, and voids between soil structural units may play an important role in chemical pollutants reaching ground water. Consequences of macropore flow (non-Darcian flow) include: 1) recharge of the ground water before the soil reaches field capacity; 2) less moisture for crop development because some of the water may move out of the influence of the root zone; and 3) the

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movement of some of the chemicals applied at the soil surface to greater depths than predicted by Darcian flow (Priebe and Blackmer, 1989; Everts and Kanwar, 1990). Chemical pollutants may bypass the biologically-active root zone through these preferential paths, thus reducing their residence time (time which would allow for degradation) before reaching the ground water (Thomas and Phillips 1979; Everts and Kanwar 1990; Oosting et al., 1987; Priebe and Blackmer 1989; Logsdon et al., 1990; and others). Leaching may occur when chemicals move from the smaller pores to the surface of the macropores (Wauchope, 1978; Thomas and Phillips, 1979; White, 1984; Germann, 1988; Shipitalo et al., 1990; Flury, 1996; Soutter and Musy, 1999; Kung et al., 2000a,b; Jaynes et al., 2001; Malone et al., 2001).

Soil macroporosity is one of the most important factors affecting pesticide movement to subsurface drains and shallow groundwater (Malone et al., 2004; Shipitalo et al., 2000; Kladienko et al., 1991; Kladienko et al., 2001). Even in tilled soils, pesticide transport can occur primarily through preferential flow paths (Levanon et al., 1993; Granovsky et al., 1993; Gish et al., 2004; Kim et al., 2005). Preferential flow is a complex process, and to add to the complexity, pesticide transport can be different through tilled and no-till soil (Gish et al., 1991; Donigan and Carsel, 1987; Elliott et al., 2000; Granovsky et al., 1993).

Many hydrologic models describing infiltration and water movement in soils are based on simplifying assumptions of homogeneity and isotropic soil conditions, thus predicting water movement by Darcy's Law (Beven and Germann, 1982). However, soils are not homogeneous and preferential flow has been commonly observed in structured soils (Everts and Kanwar, 1990; Priebe and Blackmer, 1989). The existence of preferential flow paths for water movement increases chemical transport into the soil profiles (Everts and Kanwar, 1990). A physically based model that simulates pesticide transport through tilled and no-till soils, such as the Root Zone Water Quality Model (RZWQM), requires an understanding of how soil properties, including macroporosity, are affected by tillage management. A reduced soil matrix saturated hydraulic conductivity decreases RZWQM-simulated macropore flow breakthrough time, which results in greater RZWQM-simulated herbicide concentration in percolate (Malone et al., 2003).

Although macropores provide pathways for deeper penetration of water into the soil profile than the wetting front, their overall contribution to ground water contamination may be insignificant if a fragipan layer exists. Fragipans are common in many soils of north Mississippi. This layer has very low hydraulic conductivities, brittleness, compactness, and absence of fine feeder roots in the brittle portion (Soil Survey Staff, 1975), impedes the vertical movement of water into the soil profile. Rhoton and Tyler (1990) and Römkens et al., (1986) showed higher bulk densities of the fragipan layer when compared to the layer above the pan. As bulk density increased, the number and size of pores decreased which reduced the saturated hydraulic conductivity. Römkens also noted a decrease in silt content and an increase in clay content in the deeper parts of the soil profile which would further retard Darcian flow. Lateral water movement along the surface of the fragipan is suspected. The excess water (difference of Darcian flow in layer above fragipan to that into the fragipan) either enters silt seems between columnar peds in the fragipan to continue its downward movement or exits down slope onto the soil surface to enter streams as interflow. If these silt seems are not continuous through the fragipan, the water is perched above the fragipan layer to be used by the growing crop or into the slower moving Darcian flow in the fragipan layer.

The relationships between agricultural practices and ground-water quality have not been addressed as extensively or effectively as have other pollution processes. For instance, tillage practices can have a profound effect on the amount and transport mechanism of pesticides through the soil profile (Kanwar et al., 1985). Minimum tillage practices, which leave a greater percentage of residues than conven-

tional tillage practices, leave the structure of surface soils largely intact, yield a greater amount of continuous macropores, reduce soil erosion and surface runoff, and increase infiltration. In contrast, conventional tillage practices, which include plowing, disking, and harrowing, destroy most of the preferential paths at the soil surface that reduce the number of pathways for water to move by gravity into the soil profile, increase soil erosion, and increase surface runoff. Limited field studies with various tillage practices have been conducted on the transport of chemical pollutants from the soil surface to the ground water in structured soils possessing restrictive layers such as a fragipan.

A simple approach to describing the transport of water and chemicals in a structured soil is to consider soil to be a dual porosity system (matrix flow and macropore flow) with the assumption that water movement occurs uniformly (or not at all) through the smaller pores and more rapidly through the larger macropores. Skopp (1981) suggested that pores could be classified on the basis of their function. Matrix porosity (matrix flow) was defined as that porosity carrying water and solutes slowly enough so there is extensive mixing between pores, consistent to Darcy's law and for solute transport by the convective dispersive equation. Macroporosity, a second type of water and solute transport, was defined by Skopp (1981) as that portion of soil porosity providing preferential flow paths where mixing and transfer between adjacent pore sizes was limited.

The purpose of this work was to separate the water reaching a subsurface drain during rainfall simulation into its matrix porosity and macroporosity components under different tillage conditions, using the assumption of a dual porosity model. Once the magnitudes of the two flow components were estimated, the relative importance of each in solute transport could be assessed.

2. Materials and methods

The experimental area, located on the North Mississippi Branch of the Mississippi Agricultural and Forestry Experiment Station at Holly Springs, Mississippi was arranged with four 1-m² hydraulically-isolated plots with subsurface drains installed on the fragipan surface at depth of 0.6 m. Previous to this study, the plot areas were in pasture. The soils were Loring silt loam (*Typic Fragiudalf*) overlaying a fragipan layer. Two years prior to tracer experiment, two of the four plots had 5-cm drains installed by trenching from the soil surface to the fragipan layer and backfilling with excavated material. The other two plots had 5-cm drains installed by horizontally drilling along the fragipan surface entering the plot from outside the plot area. Each drain line was intercepted at the lower end of the plot by a 15-cm diameter pipe installed vertically from soil surface to below the drain outlet outside the isolated plot area. These culverts provided access for sampling subsurface drain flow and measuring drain flow rate. The isolation of each of the four plots was with 0.38-mm (15-mil) thick plastic barrier placed in a trench surrounding each plot. The plastic barrier was from the surface to a depth of 122 cm to prevent outside subsurface water from entering the test area. The depth of the plastic barrier was approximately 0.61 m into the fragipan to prevent lateral movement of perched groundwater from the plot and to ensure collection. All plots were planted to fescue and left in pasture condition until conducting the tracer experiment.

A rain simulator was centered over each plot and used to apply a batch mixture of KBr at 250 mg Br⁻/L during the summer on the four plots. The rain simulator was designed for rectangular plots that were 1.2 m or less in width and 3.3 m in length. The sweeping motion of the two nozzles (Spraying Systems Veejet 80150) between two troughs or collectors at 3.05 m above the soil surface produced the simulated rainfall on the plot at the desired rainfall intensity. The collectors returned excess water to a reservoir for reuse. Rainfall intensity was controlled by governing the delay time between sweeps using a motor and clutch pair. The nozzles operated at 41 kPa and were positioned

1.52 m apart. At the height of 3.05 m, most simulated water drops attain terminal velocity by the time they reach the soil surface. Before rain simulation, the no-till plots had all residues removed and the tilled plots were shaped by tilling the top 10 cm of surface soil from each of the trenched and the horizontally-drilled plots. The experimental design consisted of two tillages (till and no-till), two rain events approximately 6 h apart, and two methods of establishing drains. Application of 64 mm and 38 mm of water solution was delivered to the plots at 12.7 mm/h for the first and second rain events, respectively. The tracer release began after plots reached field capacity. The day before the actual test, soil moisture was determined at various locations around and in the plots by using a time domain reflectometry probe. If the antecedent soil moisture was not at field capacity, the rain simulator was used to apply the necessary water to achieve roughly 32% moisture. During application of simulated rain event and continuation of subsurface drainage, subsurface drainage at each of the four sites was collected by placing 1-L bottles at the lower end of each drain line and collecting the water from the drains over 1-min sampling periods. Time for delivery of first sample from initial rainfall as well as volume of sample over the 1-min duration or sampling time to fill bottle were recorded. This information was used to calculate flowrate. Type of data collected included measurement of subsurface drain flow and Br^- concentration analysis of the flow at various intervals during and after the two rainfall simulations.

A hydrograph-separation technique, using a mass balance and a dual porosity model, was applied to the tracer concentration and flow rate of drainage water to estimate the macropore flow and matrix flow components of subsurface drainage. Individual hydrographs of both matrix and macropore flow were constructed.

The methods of this experiment were based on using a mass balance equation that describes the transport of a solute to subsurface drain flow:

$$Q_T * C_T = Q_D * C_D + Q_P * C_P \quad (1)$$

where

- Q_T = Total flow rate of drainage, (L^3/t),
- Q_D = Matrix flow rate, (L^3/t),
- Q_P = Macropore flow rate, (L^3/t),
- C_T = Tracer concentration in drain water, mg/L^3 ,
- C_D = Tracer concentration of matrix flow component reaching drain, mg/L^3 ,
- C_P = Tracer concentration of macropore flow component reaching drain, mg/L^3 .

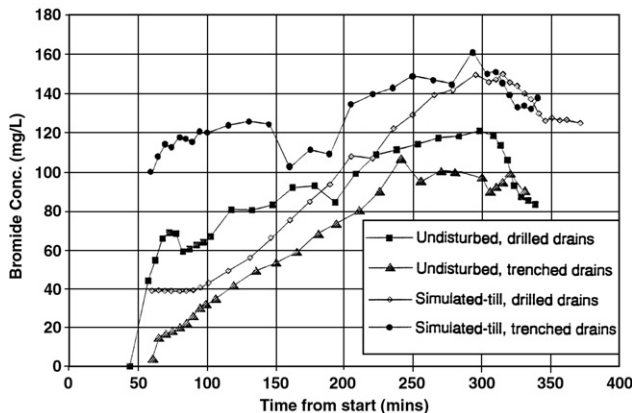


Fig. 1. Bromide concentrations (mg/L) in drain outflow of 5-h rain event.

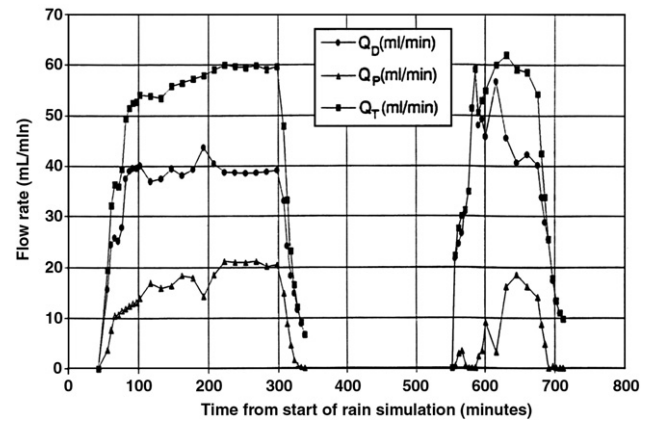


Fig. 2. Total drain flow rate (mL/min) with matrix and macropore flow components for undisturbed pasture (no-till), drilled drains during the two storms 6 h apart.

Conservation of mass yields:

$$Q_T = Q_D + Q_P \quad (2)$$

By substituting Eq. (2) into Eqs. (1), relationships of macropore flow and Darcian (matrix) flow are ascertained:

$$Q_P = Q_T * (C_T - C_D) / (C_P - C_D) \quad (3)$$

$$Q_D = Q_T * (C_T - C_P) / (C_D - C_P) \quad (4)$$

Three basic assumptions were made to solve for the two unknowns. The first assumption was that the concentration of the tracer in matrix flow, C_D , is the concentration of tracer reaching the drain that increases linearly between the initial value for C_D and the ultimate concentration for C_D at the end of simulation ($C_T = C_D$). The second assumption was that the concentration attributed to macropores, C_P , was equal to the concentration of the tracer applied in the rainfall simulation due to relatively little mixing taking place in pores contributing to macropore flow. The third assumption was that any diffusion or mixing taking place during infiltration between macropores and the surrounding soil matrix will act to decrease the concentration of tracer transported by macropore flow to the drain line resulting in minimum estimate of the volume and flow rate of the macropore flow component, Q_P . These assumptions produced two

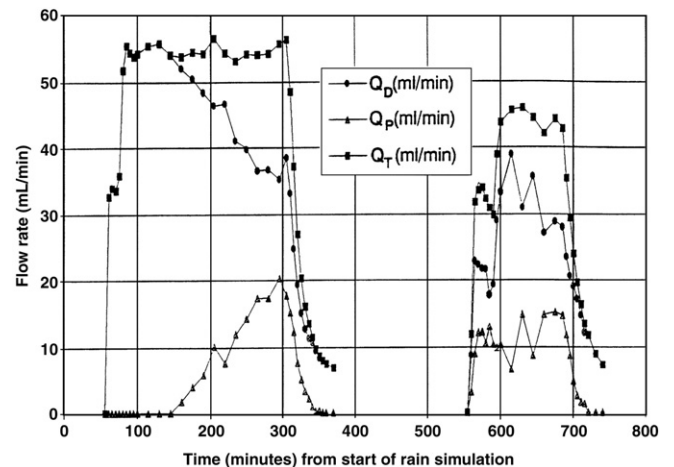


Fig. 3. Total drain flow rate (mL/min) with matrix and macropore flow components for simulated-till, drilled drains during the two storms 6 h apart.

equations with two unknowns after measuring C_T with respect to time as seen in Eqs. (3) and (4).

3. Results

Many soils in the world that are made up of silt and clay will possess both macropore and matrix flow. Those soils undergoing shrink and swell cycles, particularly those with higher clay content, will result in cracks or large macropores. As the cracks become larger, a proportionate amount of water and solute would by-pass the conventional flow associated with matrix or Darcian flow.

If either macropore or matrix flow were the only mechanism for the transport of solutes to subsurface drainage, the concentration of Br^- in drainage would be expected to increase for as long as the tracer solution was applied or until the concentration of the tracer in the drainage water reached the same concentration as that applied in the tracer solution. Fig. 1 shows Br^- concentrations measured in the drain outflow during the 5-h rain event for each treatment. The drain line was not flowing at the start of the rain event but flow began on the average of 50 min after irrigation began. During each irrigation, Br^- concentrations in drain outflow reached a peak and then began to decline. A peak in Br^- concentrations occurred between 280 and 300 min during the first irrigation. This increasing and decreasing concentration of tracer in drain outflow is consistent with a dual porosity model.

Hydrographs in Figs. 2 and 3 are the result of solving Eqs. (3) and (4) for macropore and matrix flow using the Br^- concentrations in the drainage shown in Fig. 1. Figs. 2 and 3 show the dominant mechanism for water reaching the subsurface drain line is matrix flow. Matrix flow appears to contribute the majority of the water moving to the drain line even during the early stages of the drain flow hydrographs. Initial mixing between the macropores and matrix flow, combined with high antecedent soil moisture content at the start of the experiment, may explain why macropore flow does not show greater response during the early stages of flow. Fig. 4 presents the relative contribution to drain outflow made by macropore flow during the first irrigation for each treatment. The no-till plots produced more macropore flow than the tilled plots, independent of how the drains were installed.

Total discharge and total mass of Br^- from each rain simulation are shown in Table 1. The no-till condition with the horizontal-drilled drains showed macropore flow contributed 31% and 17% of its total discharge from the 5- and 3-h storms, respectively, while the no-till condition with trenched drains showed macropore flow contributed only 16% and 9% of its total discharge for the two respective storms. However, the total discharge from the no-till condition was 6% higher for the trenched drains as compared to the horizontal-drilled drains which imply the trench may be inducing significant water movement that is non-representative of the actual water flow patterns for these

Table 1

Macropore and total discharge and mass of Br^- in drain outflow for each treatment.

	No-till Drilled drain	No-till Trenched drain	Till Drilled drain	Till Trenched drain
5-h storm				
Discharge (V)				
Macropore (ml)	4473	1635	2085	2971
Total (ml)	14,586	10,477	14,361	21,034
% Macropore	31%	16%	15%	14%
Mass ($\text{C} \cdot \text{V}$)				
Macropore (mg)	81	25	39	58
Total (mg)	118	61	121	242
% Macropore	69%	41%	32%	24%
3-h storm				
Discharge (V)				
Macropore (ml)	1206	1162	1667	1355
Total (ml)	7268	12698	6123	5762
% Macropore	17%	9%	27%	24%
Mass ($\text{C} \cdot \text{V}$)				
Macropore (mg)	16	28	44	33
Total (mg)	89	165	110	110
% Macropore	18%	17%	40%	30%

soils. The tilled plots for both drain installation procedures produced macropore discharge of 14% and 25% of the total discharge for the 5- and 3-h storms, respectively. The tilled procedures probably reduced the number of continuous macropores thus causing reduced preferential flows. Even though macropore flow contributed relatively small amounts of total drain outflow as compared to the matrix flow, preferential flow contributed on a mass basis 55% and 18% of the bromide for the 5- and 3-h storms, respectively, under no-till conditions and 28% and 35% of the bromide for the two storms under till conditions.

4. Conclusions

Matrix and macropore flow components were separated from total flow by a hydrograph-separation technique which used the assumption of dual porosity and a tracer mass balance. An estimate of the magnitude of water and Br^- transported by macropore flow to a drain line from irrigations applied by a rain simulator were shown in Figs. 2–4. These hydrographs provide an indication of the potential significance of macropore flow in transporting water and chemicals that move like Br^- through macropores to the shallow groundwater system. These procedures should be considered a minimum estimate of the quantity of macropore flow due to the simplified assumptions of all macropore flow being intercepted directly by the drain and no dilution of tracer occurs in the preferential flow channels. Macropore flow in the drainage at any time was small as compared to the matrix flow; however it contributed a disproportionate amount of Br^- tracer. These data support the concept that models used to predict mass balances using only the matrix flow will thus underestimate those chemicals that move like bromide into the soil profile.

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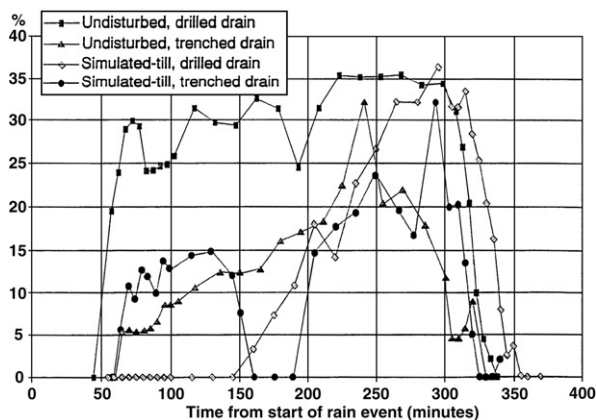


Fig. 4. Macropore flow component as percentage of total outflow during first rain event.

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